NASA ESTO
Advanced Information Systems Technology (AIST)

ESTO Earth Science Technology Office
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Earth System Digital Twins

Jacqueline Le Moigne

84th HPC User Forum
April 09, 2024

Earth Science Technology Office
within NASA Science Mission Directorate

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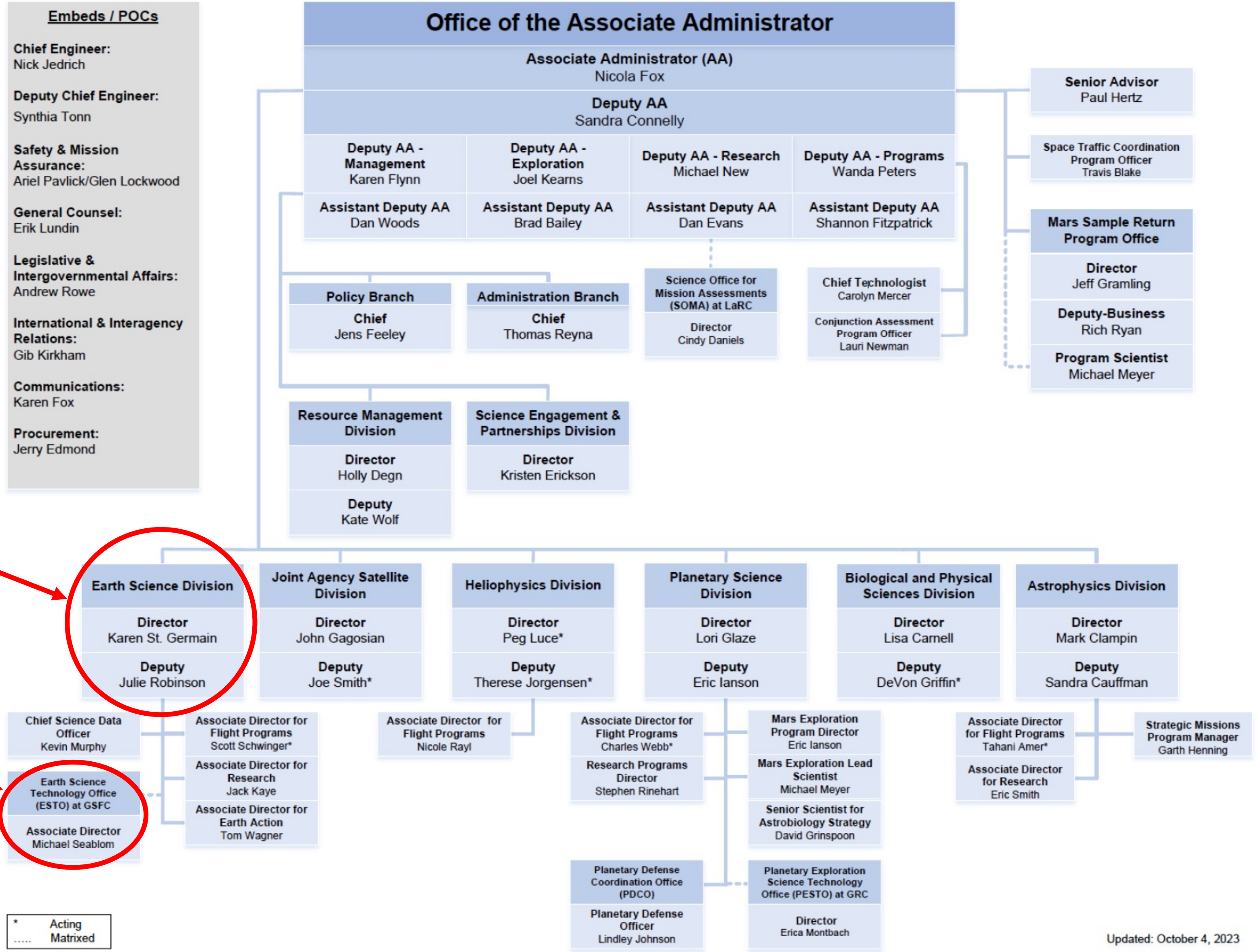

Earth Science Division

Earth Science Technology Office

Earth Science Technology Office
Main Program Elements

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ESTO manages, on average, 130 active technology development projects. Over 830 projects have completed since 1998.

Advanced Technology Initiatives: ACT and InVEST

Advanced Component Technologies (ACT)
Critical components and subsystems for advanced instruments and observing systems

Solicitation planned in *FY24 & FY25*
Average award: $1.2M (2-3 years)

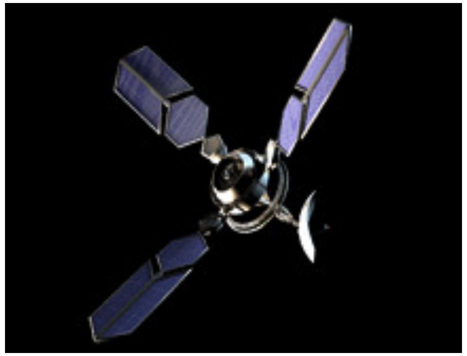
In-Space Validation of Earth Science Technologies (InVEST)
On-orbit technology validation and risk reduction for small instruments and instrument systems.

Solicitations planned in *FY23 & FY26*
Average award: $3-6M (3 years)

Instrument Incubator Program (IIP)

Innovative remote sensing instrument development from concept through breadboard and demonstration.
Average award IDD: $1.5M per year over 3 years. (instrument dev & demo)
Average award ICD: $750K over 1.5 years (Instrument concept demo)

Solicitations planned *in FY23 & FY26*
Average award: $4.5M (3 years)



Advanced Information Systems Technology (AIST)

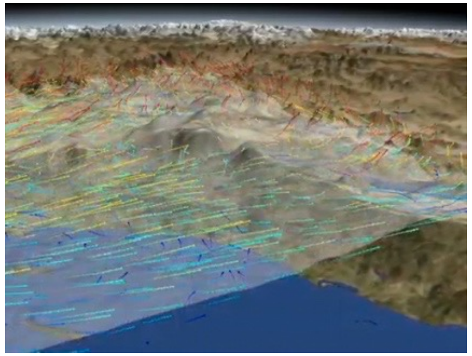
Innovative information systems for: new measurement collection through distributed sensing; Science missions ROI optimization; agile Science investigations; integrated information frameworks for mirroring Earth systems evolution and what-if scenarios.

Solicitations planned *in FY23 & FY26*
Average award: $1.2M (2 years)

Decadal Incubation

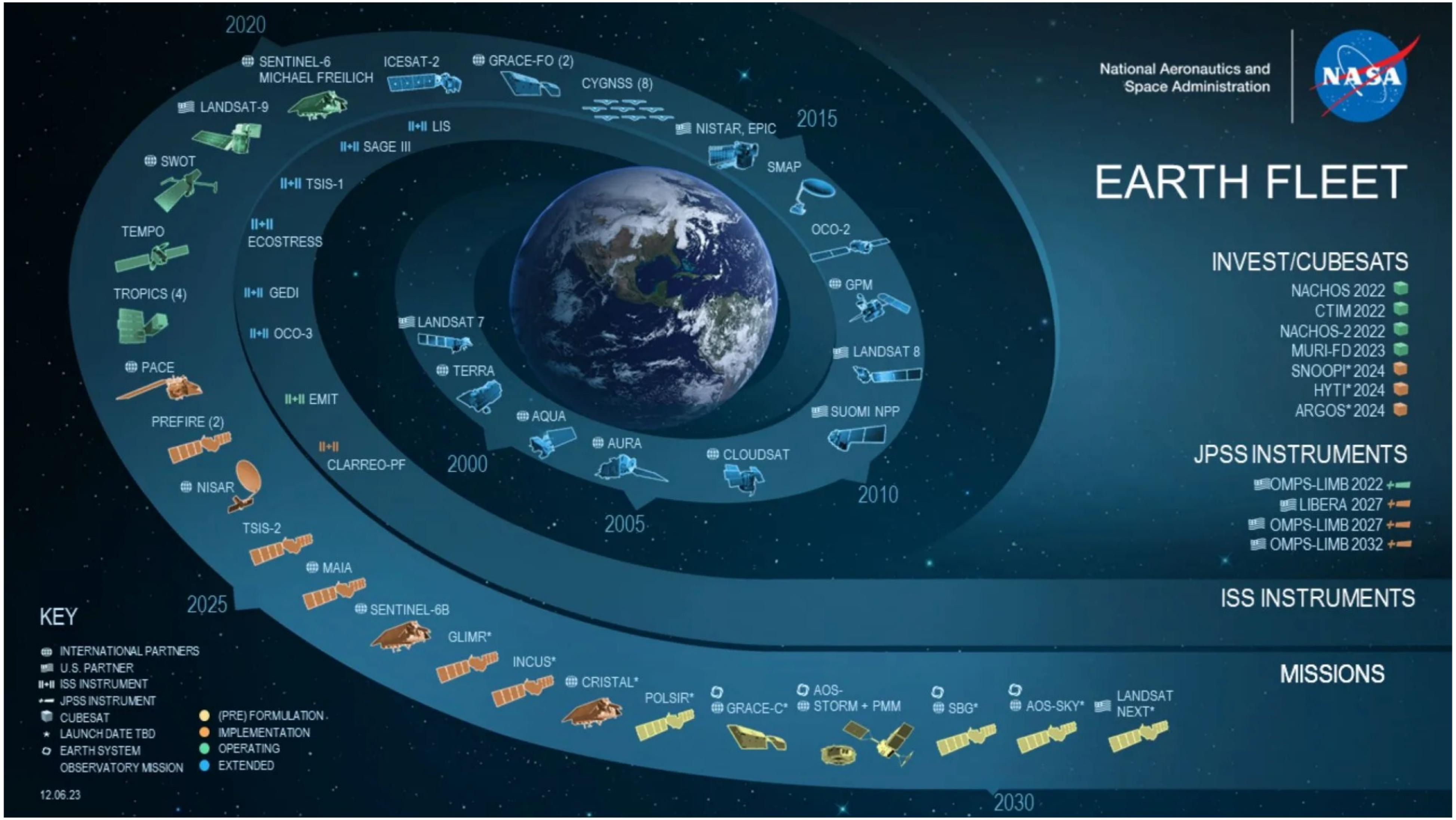
Maturation of observing systems, instrument technology, and measurement concepts for Planetary Boundary Layer and Surface Topography and Vegetation observables through technology development, modeling/system design, analysis activities, and small-scale pilot demonstrations

Solicitations planned *in FY24 and FY27*



<u>NEW since FY22:</u> **FireTech –** *Technology Development for Support of Wildfire Science, Management, and Disaster Mitigation*

Why Digital Twins in Earth Science?



NASA's Earth observing satellite fleet (as of December 6, 2023)

Why Digital Twins in Earth Science?

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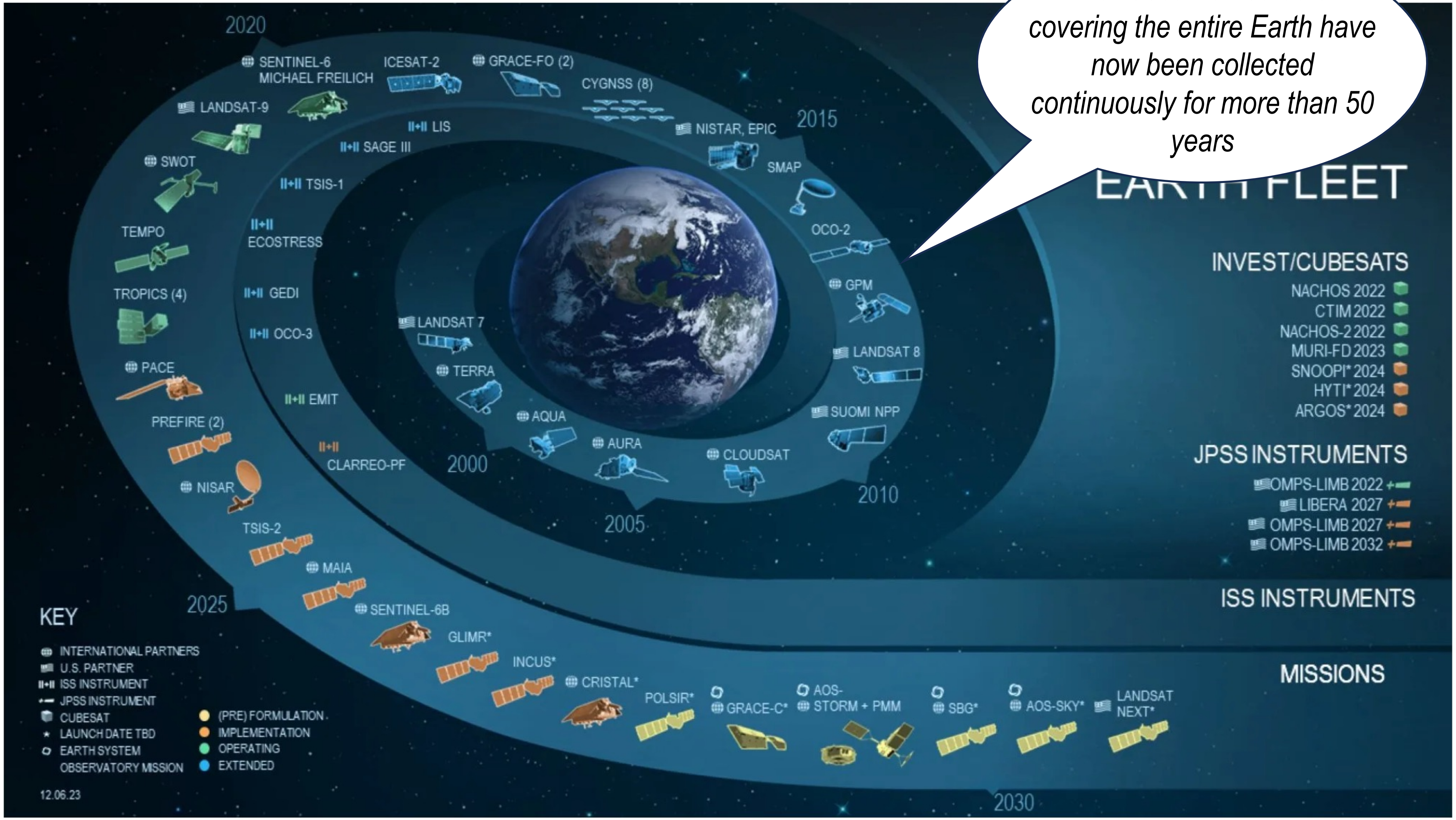
Well documented data covering the entire Earth have now been collected continuously for more than 50 years



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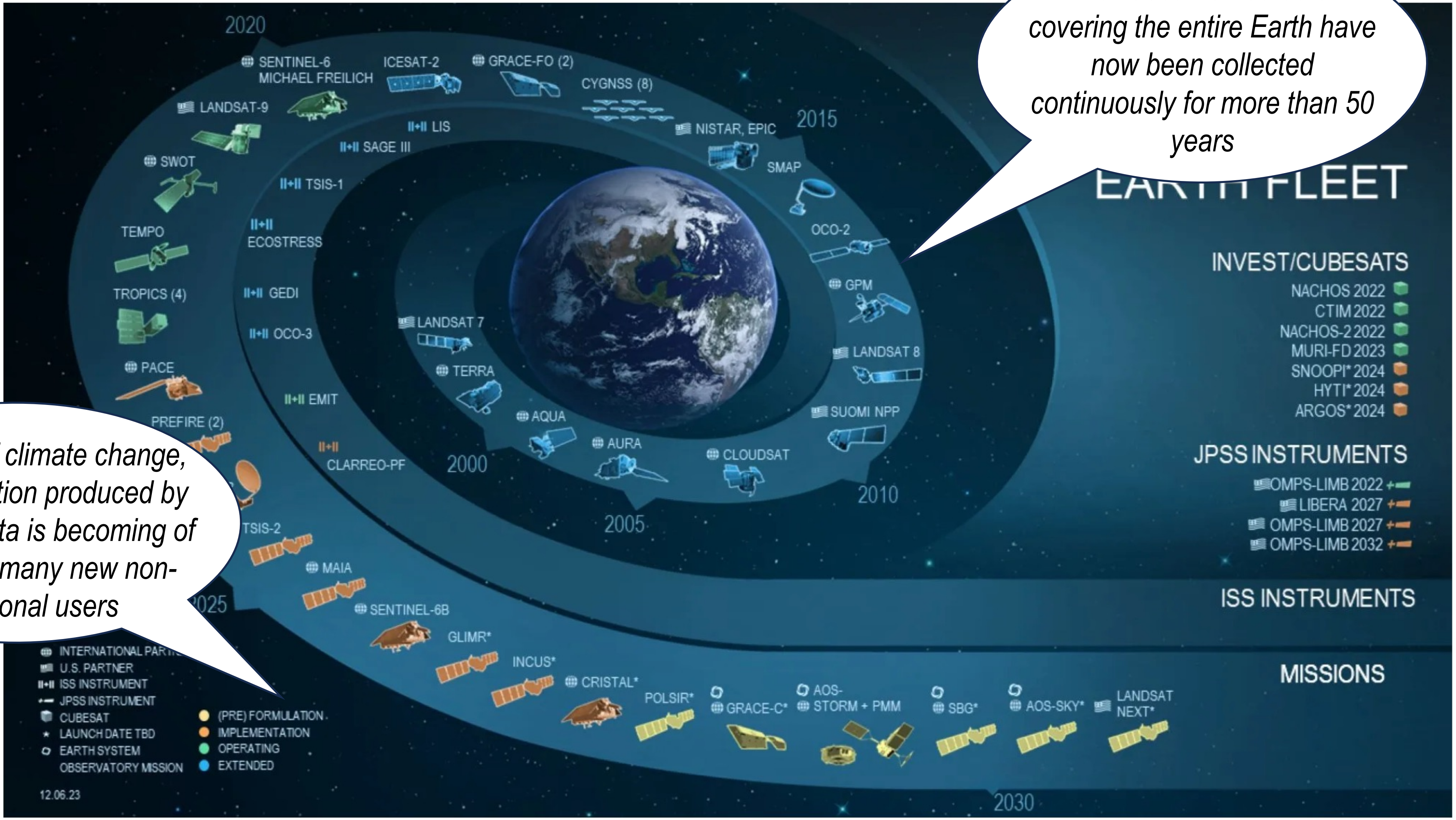
Because of climate change, the information produced by all of this data is becoming of interest to many new non-traditional users



NASA's Earth observing satellite fleet (as of December 6, 2023)

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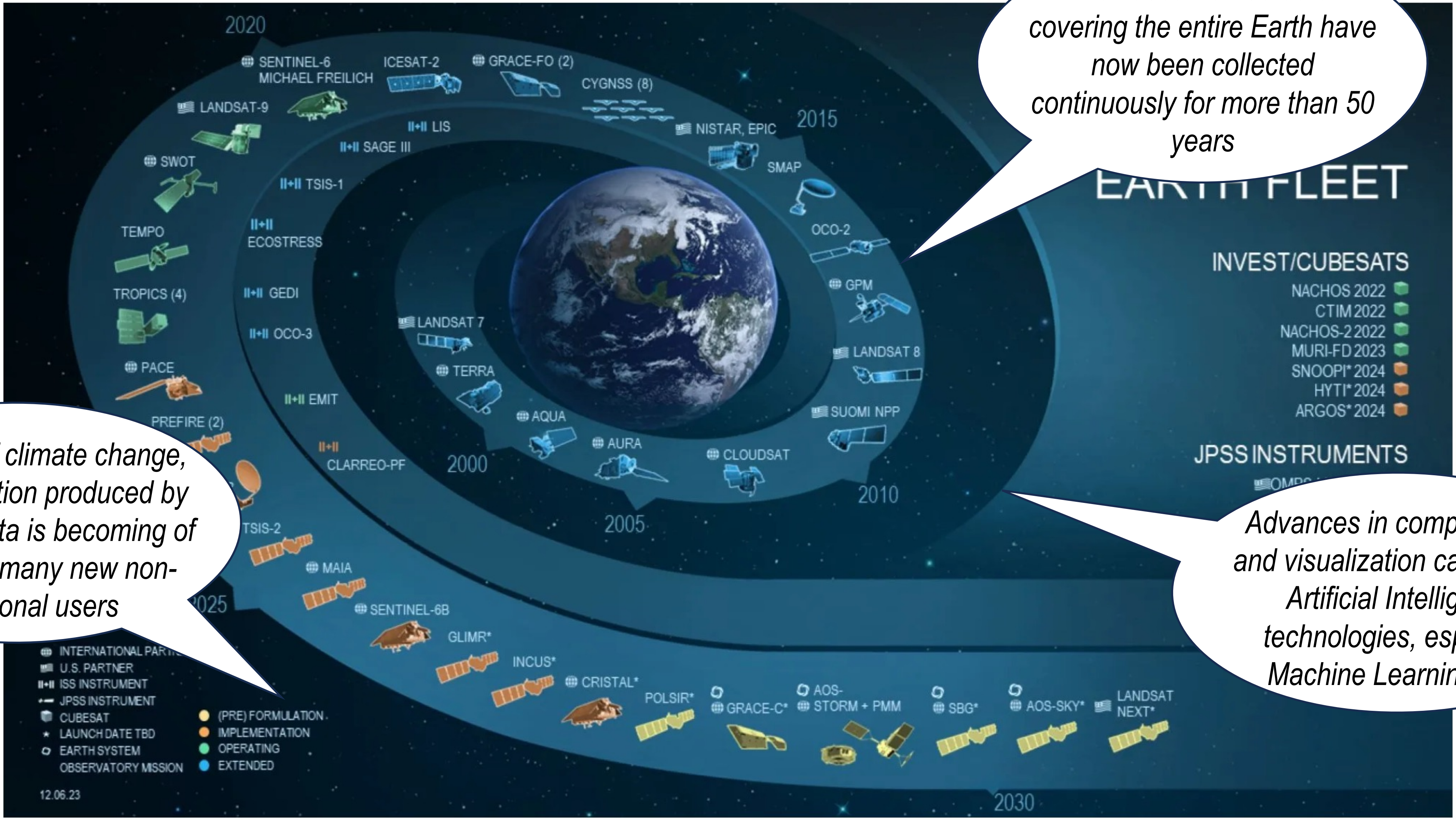
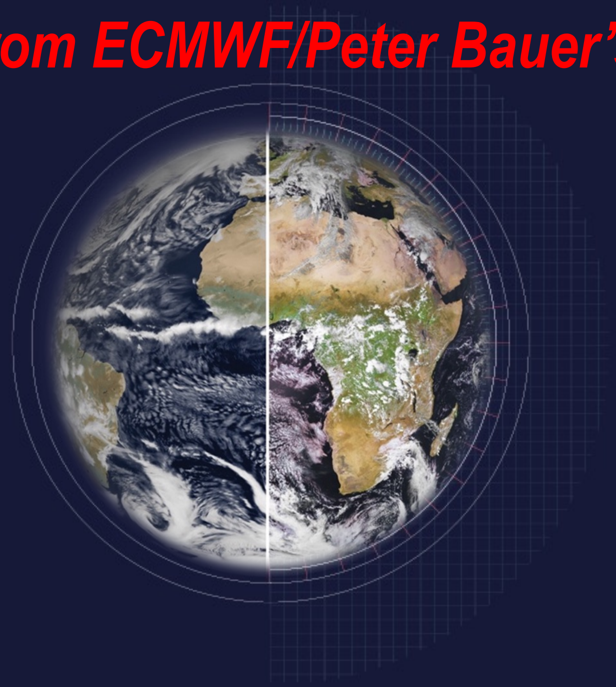
Advances in computational and visualization capabilities, Artificial Intelligence technologies, especially Machine Learning (ML)



NASA's Earth observing satellite fleet (as of December 6, 2023)

From ECMWF/Peter Bauer's Presentation _ ESDT Workshop, October 2022



Vision:

Create new, science-based information system powered by advanced digital technology to support decision making for responsibly dealing with change

Digital Twins:

- *creating more realistic models & better combination of simulations + observations*
- *integrating policy sectors (energy, food, water, health …) in workflows*
- *creating interactive configuration and information-extraction platforms & access to all data*

Challenges:

- *federating resource management across Destination Earth and existing infrastructures*
- *creating synergy across science, technology and service programmes*

Partnerships:

- *Destination Earth needs international partnerships!*
- *There will be HEP and DEP research projects helping DestinE*

Earth System Digital Twins (ESDTs) Components

Earth Systems Digital Twins (ESDTs) are information systems for understanding, forecasting, and conjecturing the complex interconnections among Earth systems, including anthropomorphic forcings and impacts to humanity.

What now?

Digital Replica . . .

An integrated picture of the past and current states of Earth systems.

What next?

Forecasting . . .

An integrated picture of how Earth systems will evolve in the future from the current state.

What if?

Impact Assessment . . .

An integrated picture of how Earth systems could evolve under different hypothetical what-if scenarios.

An Earth System Digital Twin or ESDT is a dynamic and interactive information system that first provides a digital replica of the past and current states of the Earth or Earth system, as accurately and timely as possible, second allows for computing forecasts of future states under nominal assumptions and based on the current replica, and third offers the capability to investigate many hypothetical scenarios under varying impact assumptions.

=> What Now? What Next? What If?

An ESDT includes:

- Continuous observations of interacting Earth & human systems
- From many disparate sources
- Driving inter-connected models
- At many physical and temporal scales
- With fast, powerful and integrated prediction, analysis & visualization capabilities
- Using Machine Learning, causality and uncertainty quantification
- Running at scale in order to improve our science understanding of those systems, their interactions and their applications

What is different about Digital Twins?

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1. **Continuous integration** of timely data (real- or near-real-time for some applications, “timely for others)

2. **Interactivity** with users => “playing with the models and the data” for policy/decision making and conjecturing/planning

3. Integration of anthropomorphic forcing and **impact models**

4. Heavy use of **Machine Learning**
   - Data Fusion and Data Assimilation
   - Super-Resolution/Downscaling
   - Speeding up models => higher spatial and temporal resolution possible
   - Causal Reasoning

NASA Earth Science to Action (ES2A) Strategy

NASA's Earth Science to Action strategy aligns our assets to provide actionable information for a wide range of actors and decision-makers, and to do so for a variety of impactful areas identified for their strategic importance to national and international priorities.

https://science.nasa.gov/earth-science/earth-science-to-action/

Objectives:

- **Objective 1:** Holistically Observe, Monitor, and Understand the Earth System
- **Objective 2:** Deliver Trusted Information to Drive Earth Resilience Activities

Digital Twins for Connecting Earth Science to Earth Action – *From Observations to Solutions*

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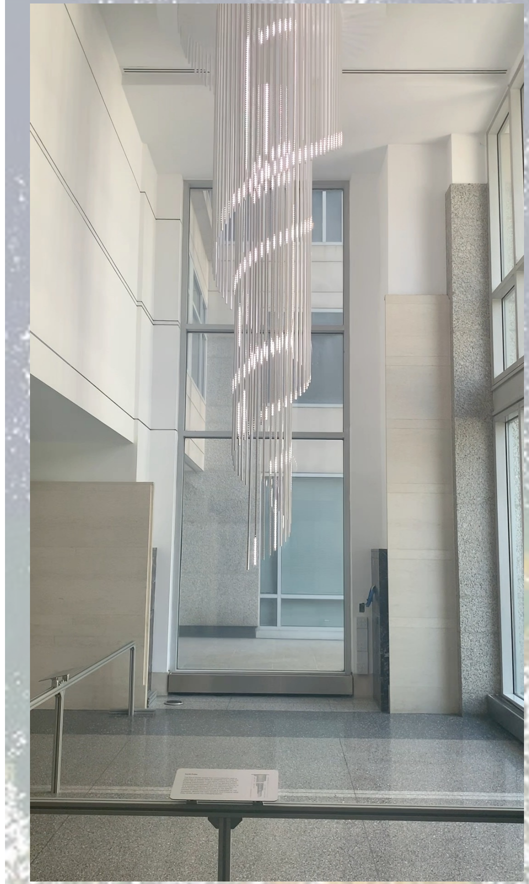
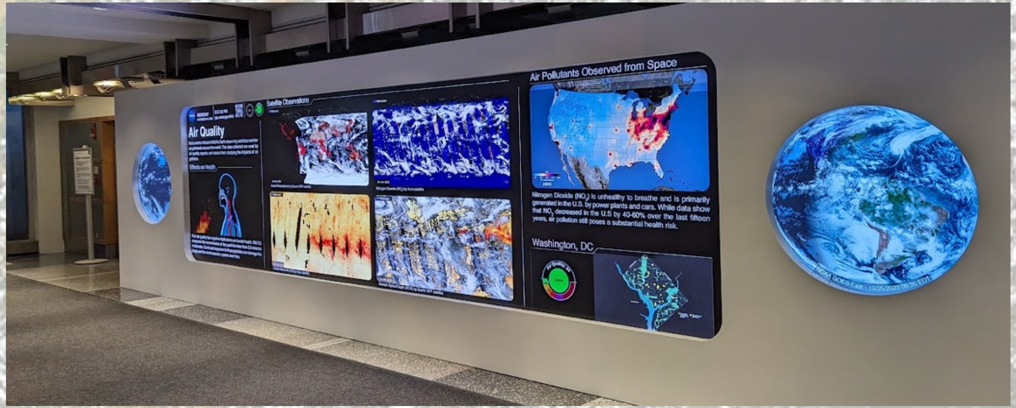
NASA's Earth Information Center

A physical and virtual space to engage and amplify the impact of scientific findings – ***showing our Earth as Science sees it***

An immersive installation to allow visitors to go inside the data



Earth Pulse display showing Near Space Network data collection



Hyperwall

Digital Twins for Connecting Earth Science to Earth Action (ES2A) – *From Observations to Solutions*

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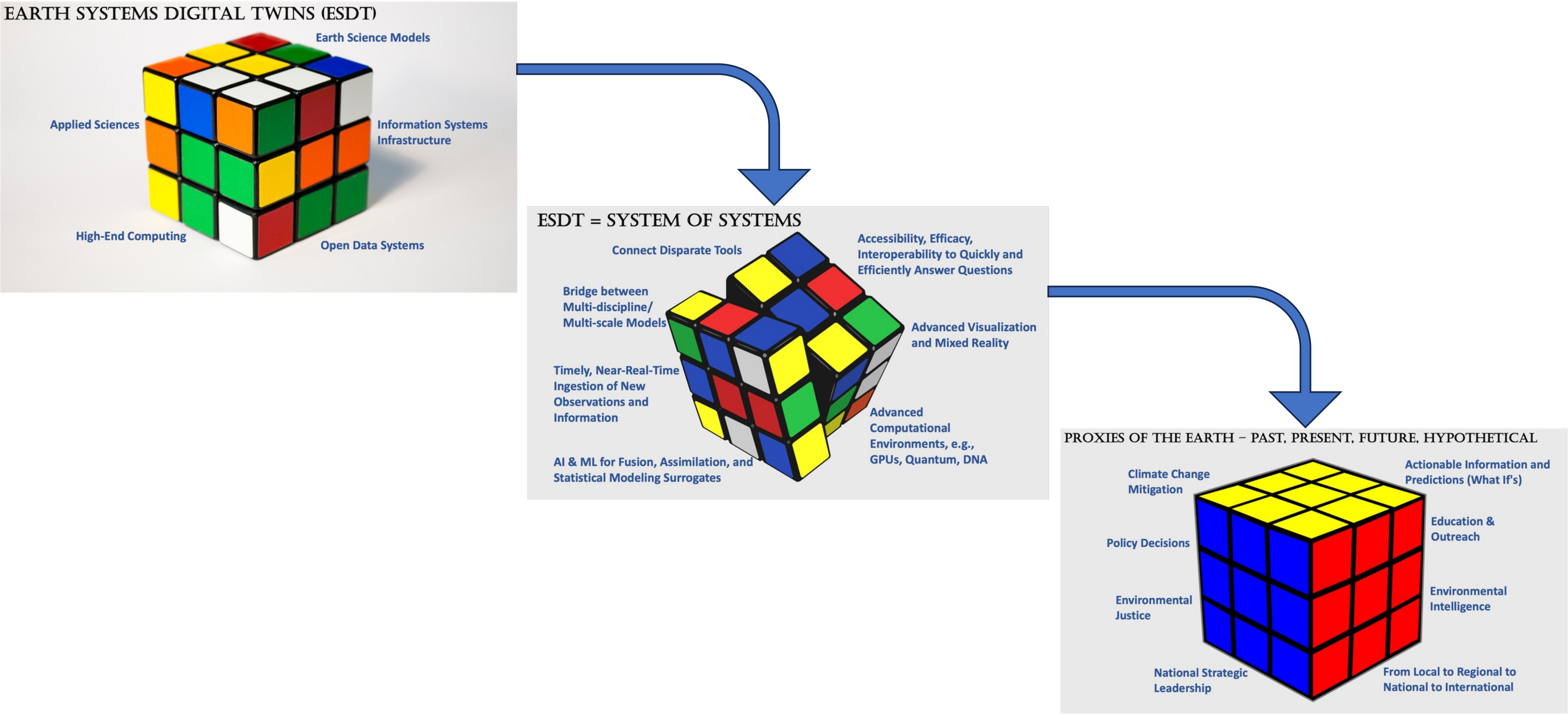

Three AIST Thrusts – *From Observations to Solutions*

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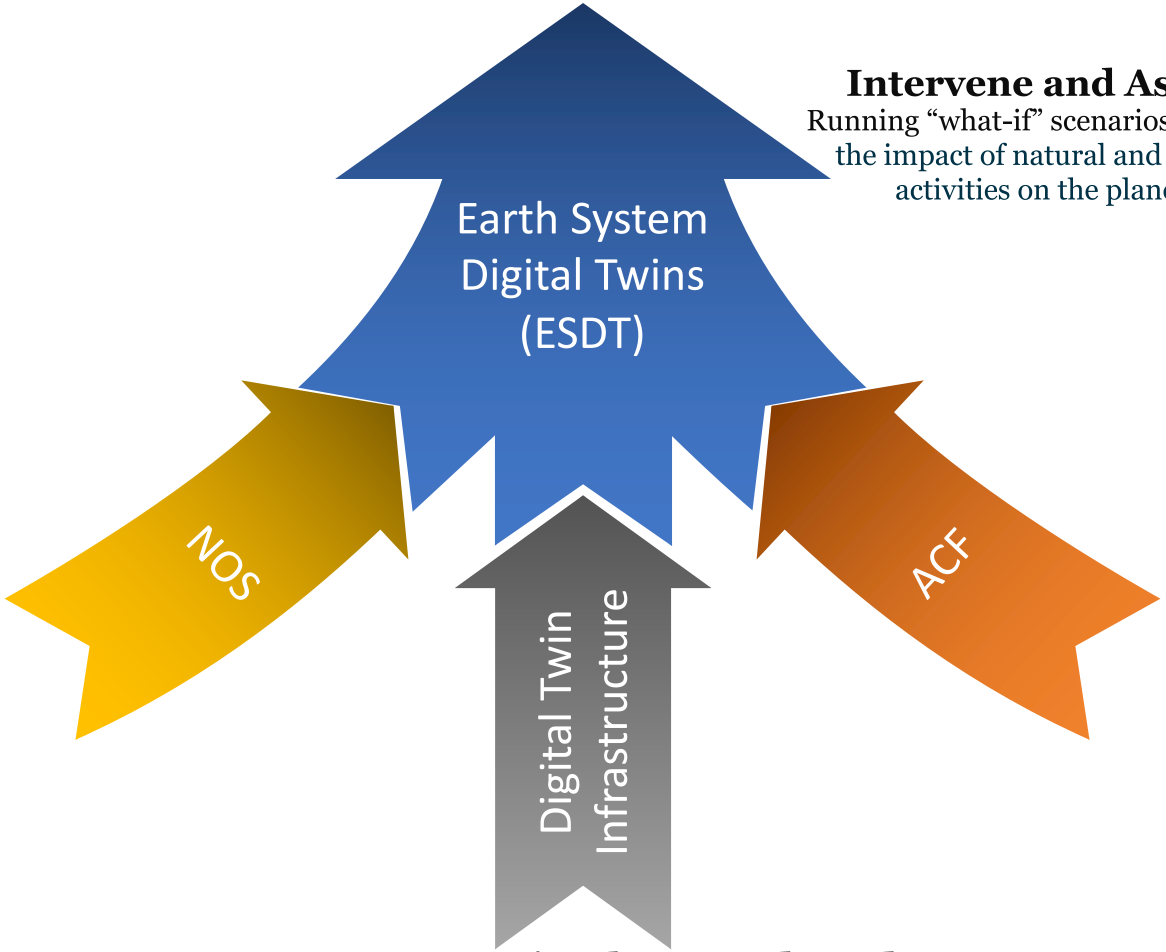


Intervene and Assess

Running "what-if" scenarios to assess the impact of natural and human activities on the planet.

Observe, Target and Coordinate

Edge and on-the-ground intelligent planning, evaluating, coordinating and operating collections of diverse and distributed observing assets

Fuse, Analyze, Share and Collaborate

Simplify access to diverse and large amounts of data, analytics & modeling tools and advanced computational resources for collaborative science

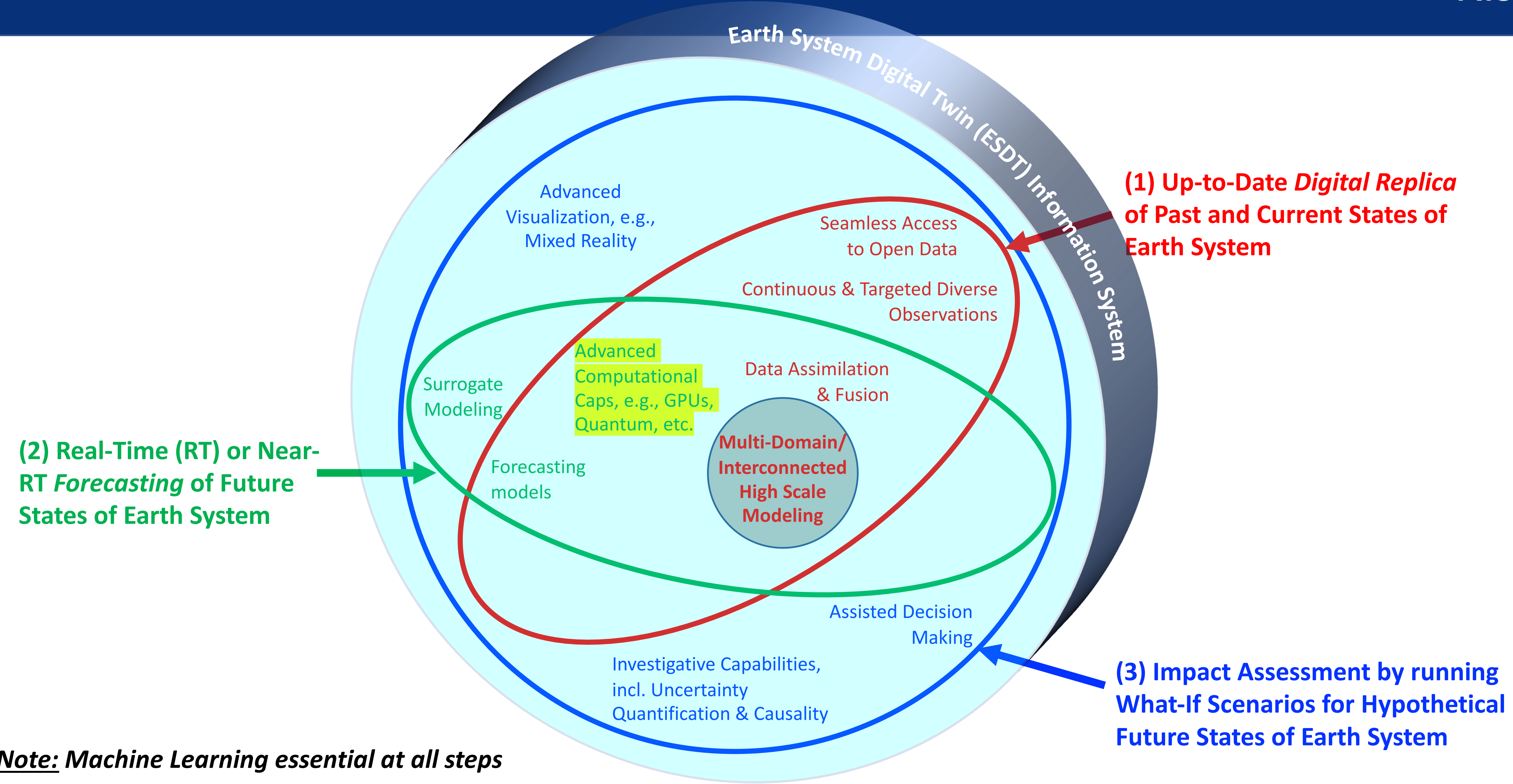
Interrogate, Simulate, Trade and Visualize

Robust tools for interrogating, assessing uncertainties & causality, and for visualization, leveraging diverse data, models and products

NOS = Novel Observing Strategies

ACF = Analytic Collaborative Frameworks

AIST ESDT Capabilities and Technologies



Note: *Machine Learning essential at all steps*

AIST ESDT Activities
https://esto.nasa.gov/AIST23/

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- **2022:** AIST-21 => 16 ESDT Projects
- **2022:** ESDT Workshop and Report
- **2023:** ESDT Architecture Framework Document
- **2023:** ESDT Standards for Interoperable Digital Twins Workshop
- **2023:** 6 Use Cases (2 additional in development)
- **2023 – 2025:** Inter-agency/International Coastal Zone Digital Twin pathfinder activity
- **2024 – 2027:** AIST-23 => Advanced technologies + 2 or 3 end-to-end prototypes
- **Collaboration** with NOAA, ESA, DestinE/ECMWF and EUMETSAT, CNES
- **Community Outreach:** Invited Sessions at AGU and IGARSS; IGARSS multi-org townhalls

ESDT Science Use Cases/Scenarios

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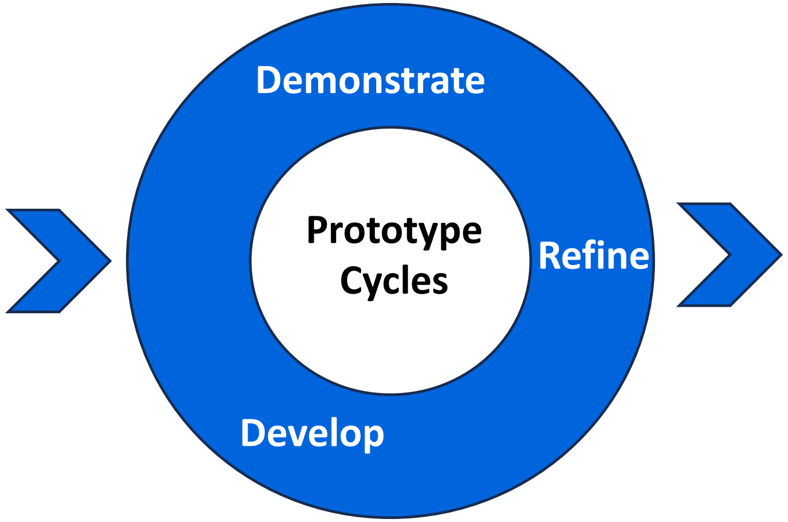
ESDT Use Case	SCOPE
Wildfires	A digital twin of Earth systems involved in wildfires to represent and understand the origins and evolution of wildfires and their impacts on ecosystem, infrastructure, and related human systems.
Ocean Carbon	An Earth system digital twin of ocean, land, atmospheric Earth systems to understand ocean carbon processes such as carbon export and ocean-atmosphere processes and coupling; land-ocean continuum and interactions with human systems; coastal ecological changes and impacts to ecosystem services; feedback processes (e.g., storm intensification and sea level rise) and impacts on coastal communities and the blue economy; assessing feasibility and impacts of various Carbon Dioxide Removal (CDR) approaches as a strategy to remove and sequester atmospheric carbon.
Water Cycle	A local or regional digital twin to understand all the complexities of the Water Cycle, how it is affected by various Earth Systems at multiple temporal and spatial scales, and how it is impacted by decision making and human influence. It would provide capabilities *such as* zooming out in time and space; helping understand water availability and origin for agriculture; how events such as floods and droughts affects life, property and infrastructure; and more generally how the effects of weather and climate variability can be mitigated under various scenarios.
Central Africa Carbon Corridors	An Earth System digital twin of "Carbon Corridors" (i.e., connected regions of protected forests/vegetation. They store carbon and maintain habitat connectivity for biodiversity) in Central Africa to: understand the current conditions; assess their ability to store carbon and promote biodiversity; forecast future conditions; conduct what-if scenarios to assess the impact of policy decisions and potential climate conditions.
Atmospheric Boundary Layer	An Earth system digital twin of the atmospheric boundary layer to provide a digital replica of the lowest portions of the atmosphere and of their processes and interactions with other systems – land, ocean, and ice surfaces – and how these interactions control exchanges with materials such as trace gases, aerosols; coupled atmospheric systems to understand underlying processes and their relationship to climate and air quality, the role of these interactions on the global weather and climate system; atmospheric systems related to greenhouse gasses (GHG), sources of pollution, and their transport in the atmosphere to understand air quality and human health impacts at multiple scales from hyper local to long term global climate projections; proper characterization of the Planetary Boundary Layer (PBL) is also critically important for modeling nighttime minimum temperatures for agricultural applications, and for prediction of wildland fire risk.
Coastal Zone Digital Twin	An Earth System digital twin of local and regional coastal zones that considers both natural and human systems to understand changes in coastal flooding severity, land and marine morphology, nutrients and water quality, ecological makeup, sea level, and the short and long-term risks to climate change adaptation, sustainable development, disaster management, tourism and recreation, quality of life, ecosystem management, and coastal infrastructure management.

ESDT Benefits to NASA Earth Science
Mapping ESDT Use Cases to ES2A Focus Areas

Current AIST ESDT Use Cases
Wildfires
Ocean Carbon
Water Cycle
Central Africa Carbon Corridors
Atmospheric Boundary Layer
Coastal Zone Digital Twin



Earth Science to Action Focus Areas
Agriculture Production
Water and Food Resources Management
Wildfire Response and Recovery
Sea Level Change and Coastal Risk and Resilience
Air Quality
Environmental Health, Water Quality and Infectious Disease
Energy and Sustainable Infrastructure
Disasters and Extreme Events
Greenhouse Gas Measurement and Monitoring
Biodiversity and Ecological Conservation
National Security
Terrestrial Carbon Accounting
Human-Ocean interactions
Stratospheric Ozone Monitoring
Society and Economic Sectors
Policy- and Decision-Making Support at the Local, State, Tribal, Federal Government and International Levels

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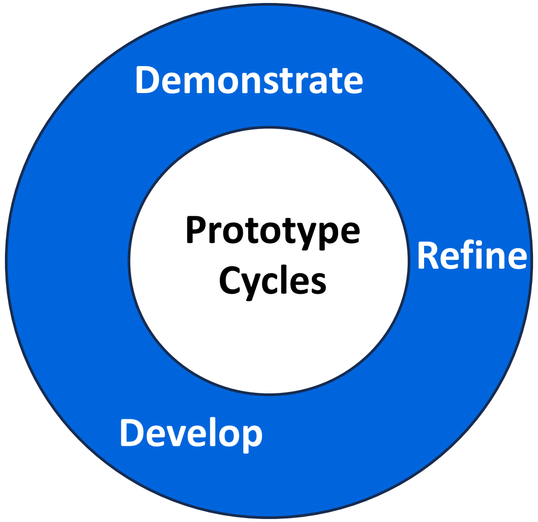

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Example – Coastal Zone Digital Twin (CZDT)

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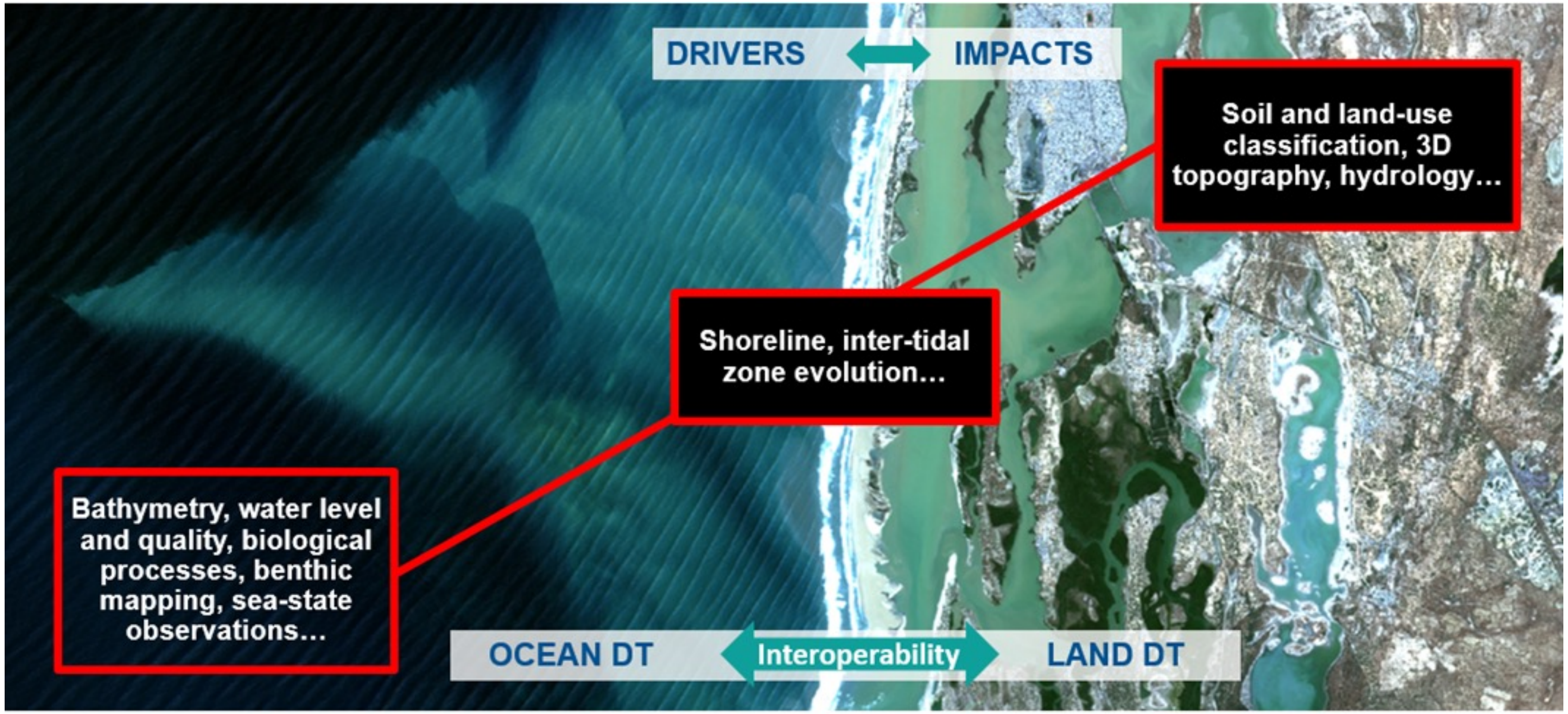
SCOPE: An Earth System Digital Twin of local and regional coastal zones considering both natural and human systems to understand changes in coastal flooding severity, land and marine morphology, nutrients and water quality, ecological makeup, sea level, and short and long-term risks to climate change adaptation, sustainable development, disaster management, tourism and recreation, quality of life, ecosystem management, and coastal infrastructure management.

What is the effect/impact of changing climate on coastal environment under various sea level and storminess scenarios?

What would be the economic health changes if flood risks were lowered? Increased?

What are the shifts in phytoplankton types under different natural/human forcings with improved HAB forecasting?



What would be the water quality changes under different water management structures/policies?

What are the impacts of management on blue carbon ecosystems to support climate mitigation and adaptation and improve resiliency to climate impacts?

What would be the changes in ecological makeup if cities reacted to increased flood risk?

What would the economic outlook be if biodiversity changed as a result of city or industry change?

How can we support cities to mitigation if flood risk increased?

What would be the flood risk changes if global temperature goals were met? Not met ?

ESDT Conceptual System Diagram

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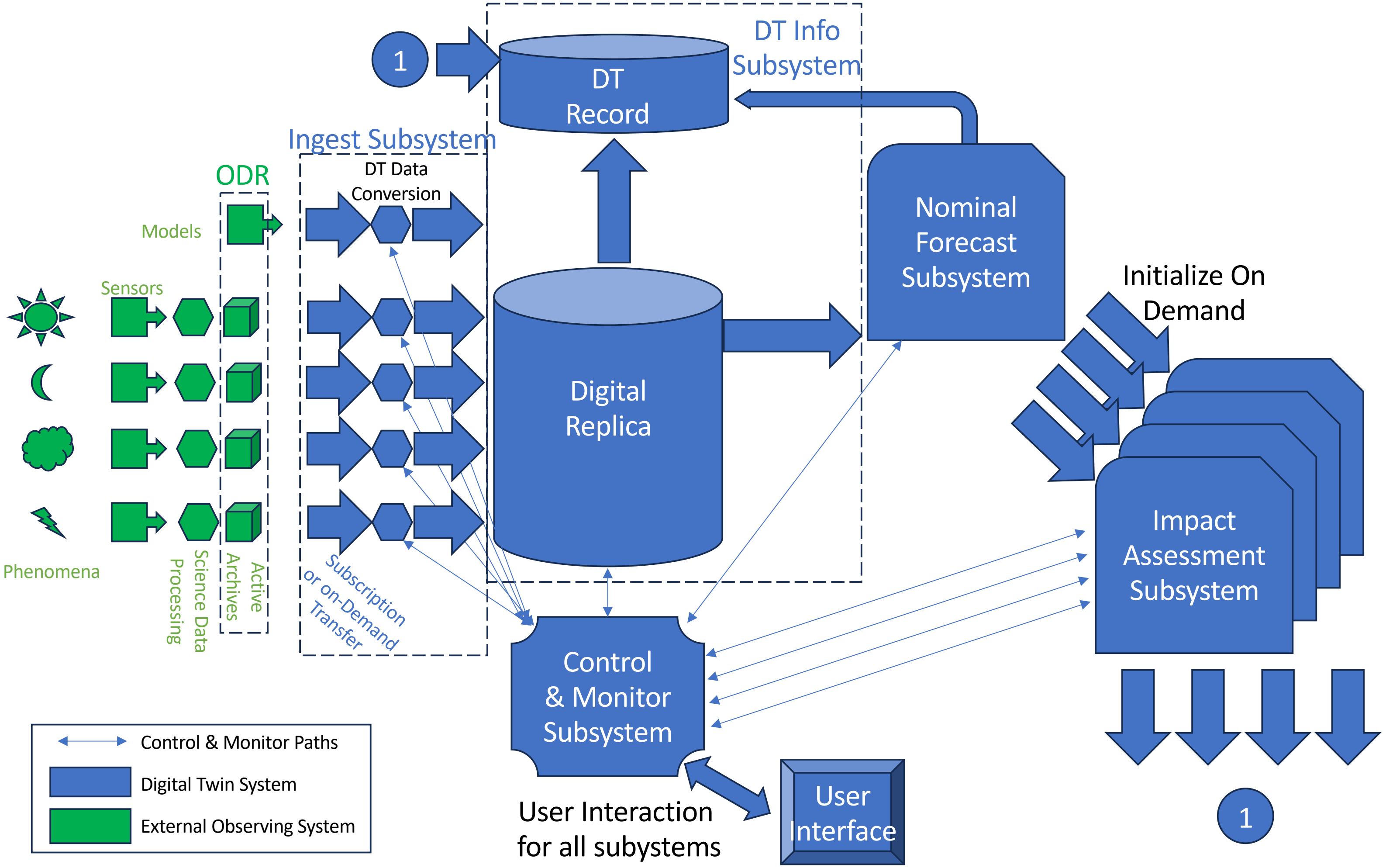
An ESDT architecture must consider the full range of components and their relationships



Functional components:

- Observational Data Repository (ODR)
- Ingest Subsystem (ISS)
- DT Information Subsystem (DISS)
- Nominal Forecast Subsystem (NFSS)
- Impact Assessment Subsystem (IASS)
- Control and Monitor Subsystem (CMSS)
- User Interface Subsystem (UISS)

Architecture design may combine components or group them differently

ESDT Architecture Framework Considerations

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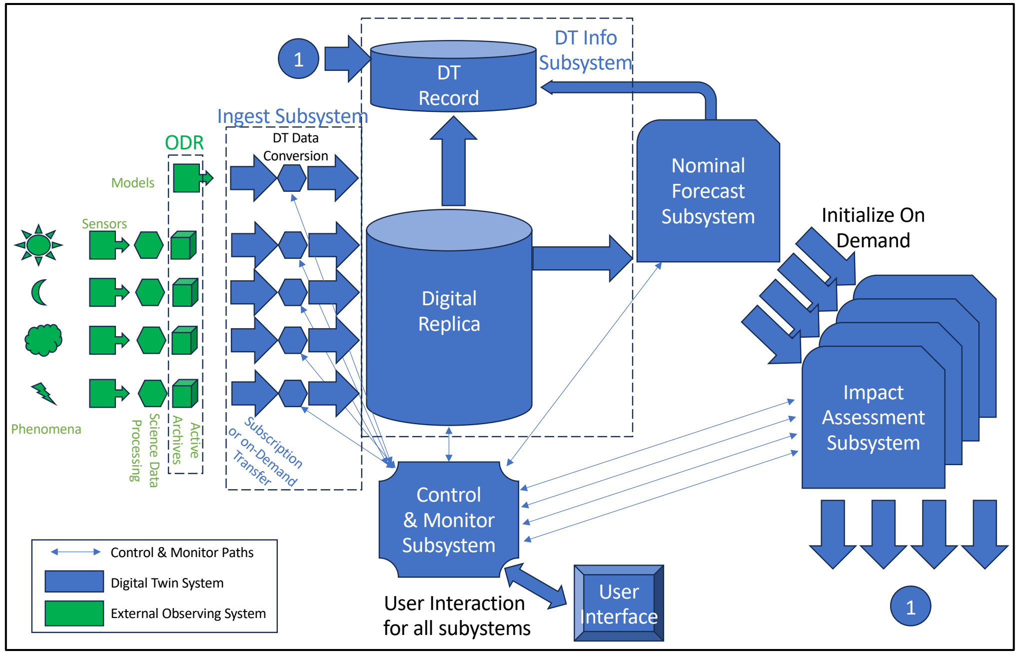
- **Consider architecture principles**
  - Modularity
  - Process automation and error checking
  - Comply with Open Source Science principles from SPD-41A
  - Permit evolution of concepts and uses and reasonable addition of new components
  - Provide the Glue to stitch together all ESD capabilities
  - Open-standard interfaces enabling opportunities for broader use
  - Interfaces for federation with other ESDTs
  - User interfaces for a range of skill levels and interests (i.e.,”from farmer to scientist”)



- **Enable component technology developers to consider their place in the overall architecture**
  - Re-use beyond a single architecture
  - Identify technology gaps and what is required to fill them

Earth System Digital Twins (ESDT)

AIST Vision

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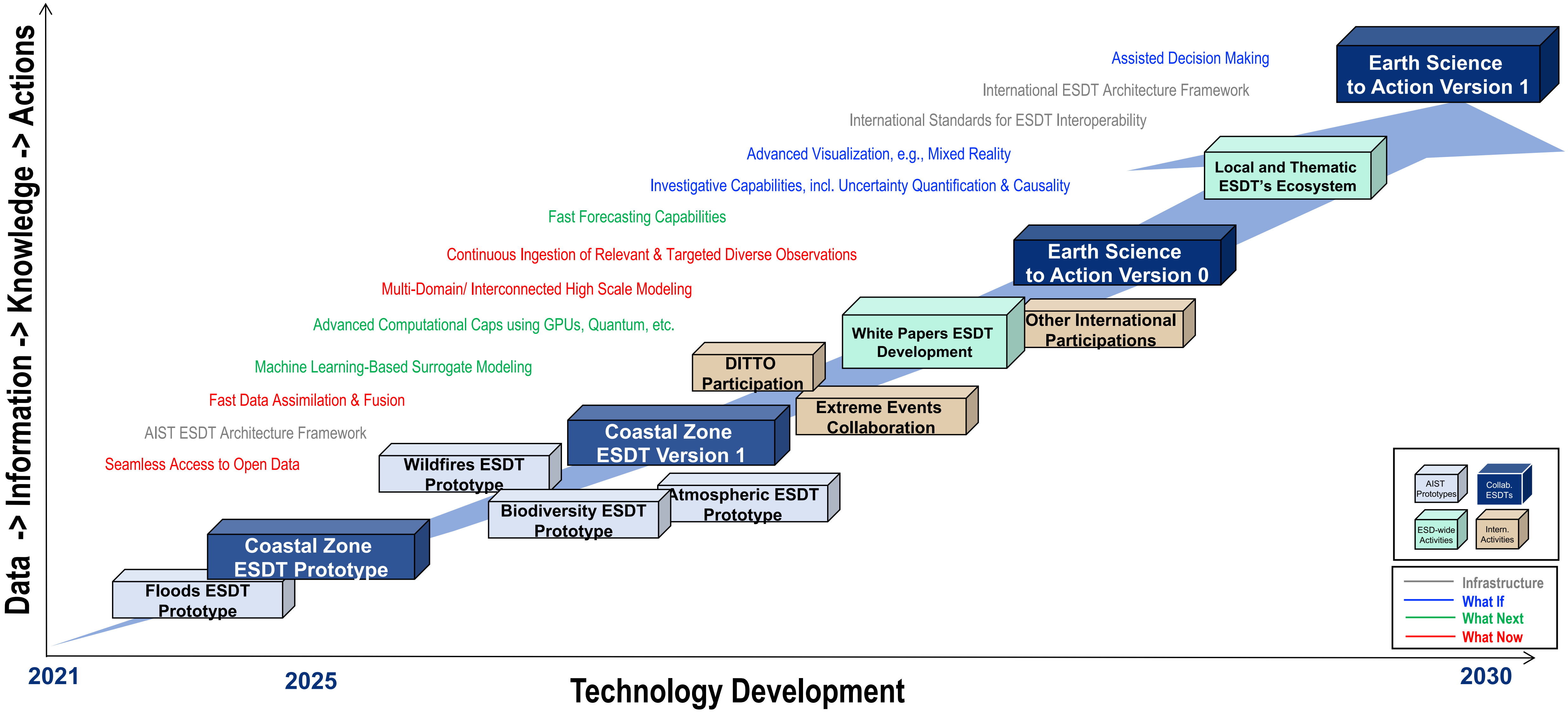


Conclusion/Next Steps

AIST-23 Solicitation Future Selections => 2 or 3 end-to-end ESDT Prototypes (2024-2027)

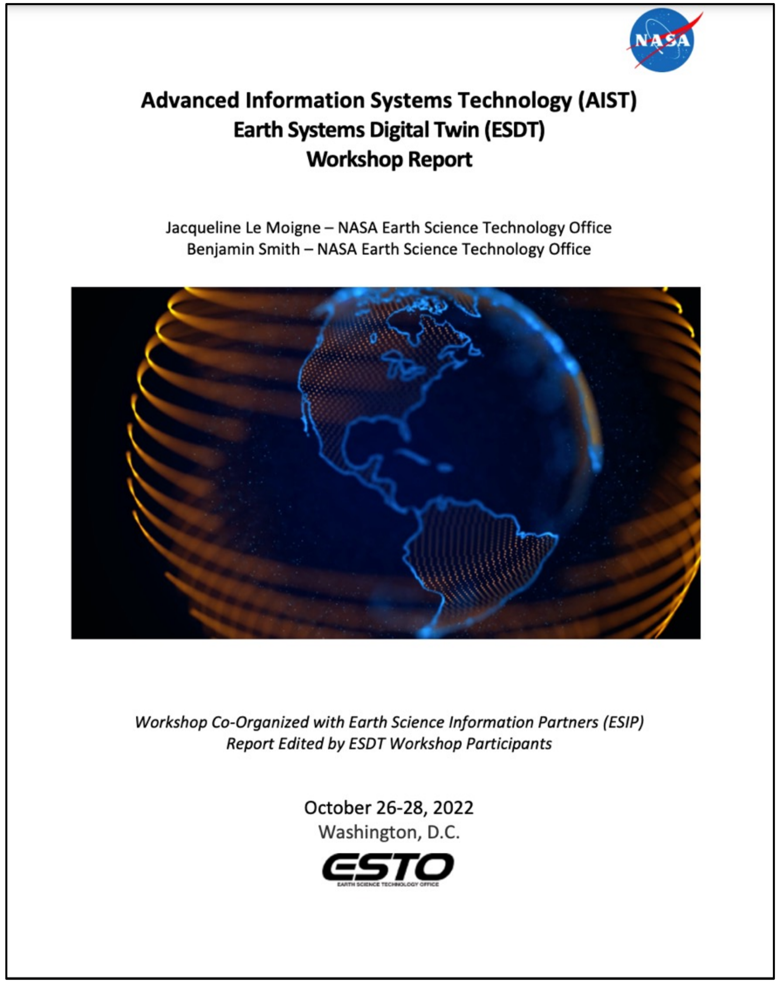
Coastal Zone Digital Twin (NASA, NOAA and CNES) => 1st Prototype expected early 2025

Some Overarching Questions:

- How will various data, models, ESDT interoperate/be federated? Which basic interfaces/standards/protocols will be required? Syntactic, semantic, legal and organizational levels
- What are the main architecture components of an ESDT?
  - What is the role of Machine Learning for ESDT?
  - What is the role of Open Science for ESDT?
  - Which computational resources will be required? Cloud, GPU's, Quantum, Neuromorphic, etc.?
  - How will continuous data will be integrated? How often will digital replica be refreshed? Which user interfaces?
- How do we validate ESDT (e.g., using historical data, etc.)? How to quantify uncertainty?
- Which sustainable digital twin governance model should be adopted to address software configuration changes, security and full life cycle management?

ESDT References on AIST Website

ESDT Workshop Report available
on AIST Website:
https://esto.nasa.gov/files/ESDT_Workshop_Report.pdf


Advanced Information Systems Technology (AIST)
Earth Systems Digital Twin (ESDT)
Workshop Report

Jacqueline Le Moigne – NASA Earth Science Technology Office
Benjamin Smith – NASA Earth Science Technology Office

Workshop Co-Organized with Earth Science Information Partners (ESIP)
Report Edited by ESDT Workshop Participants

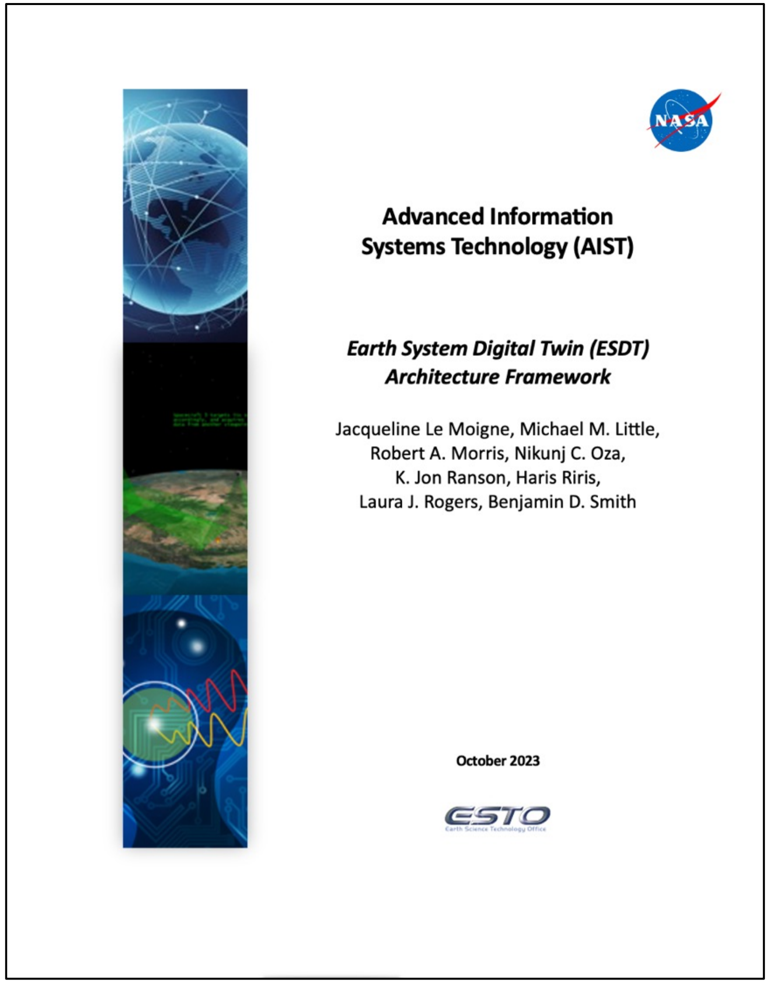
October 26-28, 2022
Washington, D.C.

Standards for Interoperable Digital Twins Workshop

September 18, 2023

- Presentations: https://esto.nasa.gov/files/AIST/ESDT%20Standards%202023.pdf
- Video: https://www.youtube.com/watch?v=qdpL0Ui-jqc

Document available
on AIST Website:
https://esto.nasa.gov/files/AIST/ESDT_ArchitectureFramework.pdf


Advanced Information Systems Technology (AIST)

Earth System Digital Twin (ESDT) Architecture Framework

Jacqueline Le Moigne, Michael M. Little,
Robert A. Morris, Nikunj C. Oza,
K. Jon Ranson, Haris Riris,
Laura J. Rogers, Benjamin D. Smith

October 2023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NASA's Earth Information Center
NASA

Back-up Slides

AIST-21 Solicitation ESDT Awards

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• Analytic Collaborative Frameworks (ACF) Towards ESDT

PI's Name	Organization	Title
Thomas Allen	Old Dominion University	Pixels for Public Health: Analytic Collaborative Framework to Enhance Coastal Resiliency of Vulnerable Populations in Hampton Roads, Virginia (VA)
Arlindo Da Silva	NASA Goddard Space Flight Center (GSFC)	An Analytic Collaborative Framework for the Earth System Observatory (ESO) Designated Observables
Thomas Huang	NASA Jet Propulsion Laboratory (JPL)	Fire Alarm: Science Data Platform for Wildfire and Air Quality

• AI and ML-based Surrogate Modeling for ESDT

PI's Name	Organization	Title
Allison Gray	Univ. of Washington, Seattle	A prototype Digital Twin of Air-Sea Interactions
Christopher Keller	Morgan State University (MSU)	Development of a next-generation ensemble prediction system for atmospheric composition
Gavin Schmidt	NASA Goddard Inst. for Space Studies (GISS)	Development of digital twin technologies for climate projections
Jouni Susiluoto	NASA Jet Propulsion Laboratory (JPL)	Kernel Flows: emulating complex models for massive data sets

AIST-21 Solicitation ESDT Awards (cont.)

- **ESDT Infrastructure**

PI's Name	Organization	Title
Thomas Clune	NASA Goddard Space Flight Center (GSFC)	A Framework for Global Cloud Resolving OSSEs
Thomas Grubb	NASA Goddard Space Flight Center (GSFC)	Goddard Earth Observing System (GEOS) Visualization And Lagrangian dynamics Immersive eXtended Reality Tool (VALIXR) for Scientific Discovery
Matthias Katzfuss	Texas A&M University (TAMU)	A scalable probabilistic emulation and uncertainty quantification tool for Earth-system models
Tanu Malik	De Paul University	Reproducible Containers for Advancing Process-oriented Collaborative Analytics

- **ESDT Prototypes**

PI's Name	Organization	Title
Rajat Bindlish	NASA Goddard Space Flight Center (GSFC)	Digital Twin Infrastructure Model for Agricultural Applications
Milton Halem	*University of Maryland, Baltimore County (UMBC)*	*Towards a NU-WRF based Mega Wildfire Digital Twin: Smoke Transport Impact Scenarios on Air Quality, Cardiopulmonary Disease and Regional Deforestation*
Thomas Huang	NASA JPL, GSFC and LaRC	Integrated Digital Earth Analysis System (IDEAS)
Craig Pelissier	Science Systems and Applications, Inc. (SSAI)	Terrestrial Environmental Rapid-Replicating Assimilation Hydrometeorology (TERRAHydro) System: A machine-learning coupled water, energy, and vegetation terrestrial Earth System Digital Twin
Alex Ruane	NASA Goddard Inst. for Space Studies (GISS)	An Urban Information System to Assess Neighborhood Climate Risk and Daily Exposures in Cities

Example – *Coastal Zone Digital Twin (CZDT)*

In collaboration with NOAA and CNES

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Scope		An Earth System Digital Twin of local and regional coastal zones that considers both natural and human systems to understand changes in coastal flooding severity, land and marine morphology, nutrients and water quality, ecological makeup, sea level, and short and long-term risks to climate change adaptation, sustainable development, disaster management, tourism and recreation, quality of life, ecosystem management, and coastal infrastructure management. *The CZDT, while global in extent, will initially consider a variety of test locations (e.g., west coast of France, west coast of Africa, the east coast of the United States, selected islands) to provide a range of hydrological, ecological, and sociological conditions.*
Capabilities	**Digital Replica *(What-Now)***	Digital replica of the current state of coastal systems to understand hydrological extremes and flooding; nutrient and pollutant levels including water quality parameters (physical/optical and chemical); topography and bathymetry; terrestrial and marine ecology; near-sea and in-sea infrastructure; and sea level at multiple spatiotemporal scales.
	Forecast *(What-Next)*	• Coastal morphology evolution of coastal morphology without further forced intervention. • How and at what rate will near shore vegetation and, more generally, coastal habitats evolve. • Changes in water quality, including nutrient runoff changes from natural variability and human interventions (e.g., urban, agriculture) that trigger harmful algal blooms (HAB). • Future states of tidal, storm, and combined flood events, and how they interact with human systems. How flooding, nutrient quantity or quality, water quality, ecology will change, and how coastal habitats/communities may shift.
	Impact Assessment *(What-If)*	What-if scenarios where human interventions are incorporated into responses to various environmental (sea-level and wave) forcing scenarios (e.g., relocate coastal settlements) • Effect/impact of changing climate on coastal environment under various sea level and storminess scenarios. • Water quality changes under different water management structures/policies. • Shifts in phytoplankton types under different natural/human forcings with improved HAB forecasting. • Impacts of management on blue carbon ecosystems to support climate mitigation and adaptation and improve resiliency to climate impacts. • Support cities to mitigation if flood risk increased. • Which flood risk changes if global temperature goals were met? Not met?. • Economic health changes if flood risks were lowered? Increased?. • Changes in ecological makeup if cities reacted to increased flood risk?. • Economic outlook be if biodiversity changed as a result of city or industry change?

Example – *Coastal Zone Digital Twin (CZDT)*

In collaboration with NOAA and CNES

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Earth Systems	• Hydrodynamics (e.g., water levels, waves, river run-off), nearshore bathymetry and topography, 3D LCLU (land cover use) • Water color and quality, bathymetry, seabed, algae, foreshore vegetation, biodiversity, LCLU near the coast. • Land surface, hydrology, lakes, rivers, ocean, estuary, water quality models and products • Ocean (sea-level, water quality, tides), atmosphere (storms and extreme rainfall), and land (vertical land movement, LCLU, and shoreline change) • Ecology; Climate; Weather; Hydrology; Socio-economic
Human Systems	• Human systems involved in the CZDT (infrastructure, agriculture, power, etc.) • In-situ observations, socio-economic data, local/governmental data, model outputs
Resources	• Remote sensing missions/instruments : Landsat 8-9, Copernicus/Sentinel-1-2-3, Harmonized Landsat/Sentinel (HLS), SWOT, CFOSAT, Optical Very High Resolution (VHR) (Pleiades, Pleiades-NEO, MAXAR, Planet,…), ICESat 2, GEDI, VIIRS, DESIS, Airborne systems (e.g., NAIP, GLiHT, UAVSAR, AVIRIS-NG), etc. • Variables LCLU (built-up area, vegetation, natural habitat), precipitation, groundwater, streamflow, soil moisture, snow, water (quality, temperature, seabed, land surface), Bathymetry-Topography continuum (Bathymetry, shoreline, OER - topographical data, IGN LIDAR-HD, digital elevation model, digital terrain model), ecological (marine and terrestrial biodiversity, habitats), • In-situ : IoT flood sensors, tidal gages, networks, Surface truth • Socio-economic and local/governmental data : social (population), infrastructures (ports/harbors/seawalls), in situ assets, protected areas, building-parcel fabric • Models and derived data : sea level rise/change and flood models, climate/weather data and projections (precip/wind speed/temp/storm surge), oceanographic (tide, current, wave height), agriculture, forest, marsh, blue carbon ecosystem models/ changes in species, biodiversity, biomass, productivity . • Future-focused decision support systems (e.g.,Geodesign)

ESDT Workshop Summary

- Same digital replica can address needs of multiple users at various resolutions and for various applications
  - Scientific experts: ESDT capabilities built around ESMs
  - Science and applications users: more accurate forecasts and what-if simulations from varying initial and impact conditions.
  - Decision makers: what-if capability enables an exploration of alternatives and their impact on Earth systems and human activities, while the digital replica and forecasting capabilities provide a comprehensive interactive environment for understanding and monitoring current conditions and their evolution.
  - General public: ESDT inform daily activities and understand our changing planet.
- Global vs. local, multi-domain vs. thematic (e.g., some domains such as Climate or Weather will require a global Digital Twin while science areas such as Biodiversity might be more local)
- Overall, could imagine a future "web" of Digital Twins co-existing in a hierarchy or in a network, and capable of being connected or federated depending on the needs.
- Challenges of building optimal digital twins:
  - Interoperability, including standards and protocols to be built from the beginning: at syntactic, semantic, legal and organizational levels
  - How to organize each digital replica, including various types of raw data, Analysis Ready Data (ARD) and information, and using various solutions, including Data Cubes, Data Lakes, pointers, or on demand
  - Type and level of interactivity and refresh rate, visualizations and human interfaces
  - Advanced technologies in Machine Learning, explainability, uncertainty quantification, validation, etc.

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